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Ultra-High Aggregate Bandwidth Two-Dimensional Multiple-Wavelength Diode Laser Arrays

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13. ABSTRACT (Maximum 200 words)

Two-dimensional (2D) multi-wavelength vertical cavity surface emitting laser (VCSEL) arrays is promising for ultrahigh aggregate capacity optical networks. A 2D VCSEL array emitting 140 distinct wavelengths was reported by implementing a spatially graded layer in the VCSEL structure, which in turn creates a wavelength spread. In this program, we concentrated on novel epitaxial growth techniques to make reproducible and repeatable multi-wavelength VCSEL arrays. Our approach to fabricate the spatially graded layer involves creating a nonuniform substrate surface temperature across the wafer during the growth of the cavity spacer region using the fact that the molecular beam epitaxy growth of GaAs is highly sensitive to the substrate temperature. We are investigating growth with the use a patterned spacer (either a Ga or Si substrate) placed in-between the substrate and its heater. We have calculated the temperature distribution on such wafers to guide our experiments. We also built a reflectivity measurement apparatus that is capable of mapping a 2" wafer with a 100 μm diameter resolution for diagnosing our wafers. In this first six-month report, we present our calculations, the various experimental results, and a discussion on future directions.

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A. INTRODUCTION

Two-dimensional (2D) multi-wavelength vertical cavity surface emitting laser (VCSEL) arrays is promising for ultrahigh aggregate capacity optical networks with the use of wavelength-division-multiplexing (WDM). Such laser array can also be used as one source with the unique capability of wavelength-synthesizing signals for information security. Previously, a 2D VCSEL array emitting 140 distinct wavelengths was reported [1] using the idea of implementing a spatially graded layer in the VCSEL structure, which in turn creates a wavelength spread over an array. In this program, we concentrated on a novel epitaxial growth technique to make reproducible and repeatable multi-wavelength VCSEL arrays.

Our approach to fabricate the spatially graded layer involves creating a nonuniform substrate surface temperature across the wafer during the growth of the cavity spacer region. Using the fact that, during an molecular beam epitaxy (MBE) crystal growth, the GaAs growth rate is highly sensitive to the substrate temperature above 650°C [2], a GaAs/AlGaAs tapered waveguide was previously reported by Bossi et. al. [3] As much as 20% difference in GaAs growth rate was obtained between the layers grown on the hotter and colder surfaces, which was estimated to be resulting from a surface temperature difference of 40°C. Although promising, Bossi's technique involves machining one permanent step in the sample holder, which is not suitable for making repeatable patterns on a wafer.

In this program, we are investigating methods to create a repeatable temperature-dependent growth patterns. In particular, we are investigating growth with the use a patterned spacer (either a Ga or Si substrate) placed in-between the substrate and its heater. We have performed a calculation to model the temperature distribution on such wafers to guide our experiments. The test structure we grew typically consists of a passive GaAs cavity with Bragg reflectors (10.5 pairs on the substrate side and 8 pairs on the top) consisting of quarter-wave AlAs/GaAs layers designed at 950 nm. We have also built a reflectivity measurement apparatus that is capable of mapping an entire 2" wafer with a 100 μm diameter spatial resolution. This setup was essential for diagnosing our growth experiments. In this first six-month report, we present our calculations, the various experimental results, and a discussion on future directions.

B. SUMMARY OF PRINCIPAL ACCOMPLISHMENTS

1. Modeling

1.1 Cavity Design

Figure 1 shows the calculated reflectance spectra of a passive Fabry-Perot (FP) cavity with its central GaAs layer thicknesses being 240 nm, which is the standard design of one-wavelength thick, and 300 nm, which is 25% thicker than the standard. This calculation gives a realistic estimate of the FP mode shift we can achieve across the wafer. For a 25% growth rate variation we can expect a lasing wavelength difference of over 50 nm. The question that remains is how sharp of a temperature profile we can expect to achieve, which will determine the minimum spacing of the devices. In the next section we estimate the temperature profile along the wafer surface given a temperature gradient on the back side.

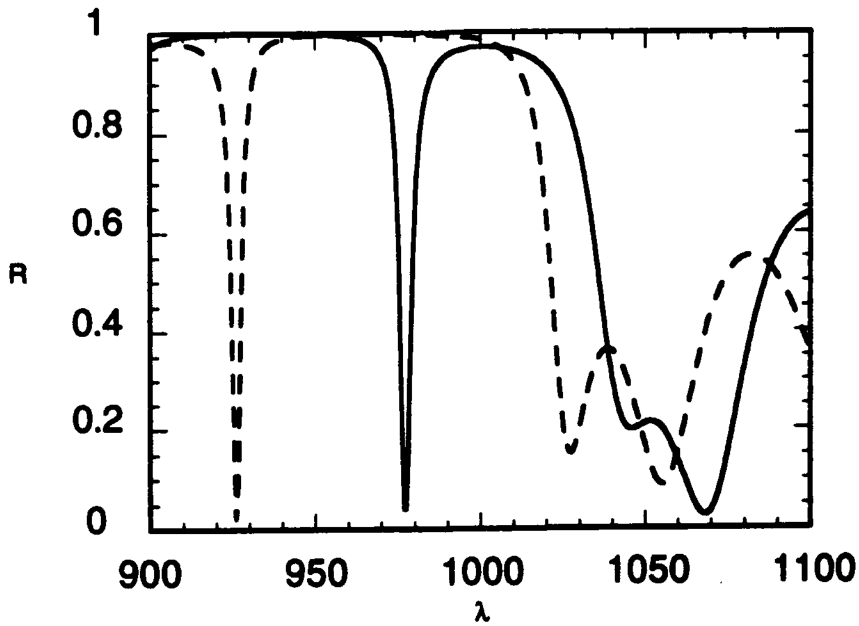

Fig. 1 The calculated reflectivity spectrum of a passive Fabry-Perot cavity with cavity thicknesses of 240 nm (dashed line) and 300 nm (solid line).

1.2 Estimate of Surface Temperature

We use the following simple model to estimate the surface temperature profile. Given a temperature profile on the back side of the wafer one can calculate the temperature profile at the substrate surface by solving the steady state heat equation

$$\Delta T(x,y,z) = 0$$

where Δ is the Laplacian operator with appropriate boundary conditions. It is the surface temperature that will determine the GaAs growth rate. As a first order approximation in one dimension, we consider an infinitely thick wafer with fixed temperature boundary conditions on the back side given by

$$T(x,0) = T_2 \quad \text{for } |x|<L/2$$

$$T(x,0) = T_1 \quad \text{for } |x|>L/2$$

This problem can be solved analytically using conformal mapping techniques [4], and the solution is

$$T(x,y) = T_1 + (\delta T/\pi) \text{Arctan}\{Ly/[x^2 + y^2 - (L/2)^2]\}$$

The result of this calculation is shown in Figure 2. As we move away from the x axis, i.e. increasing y, the temperature profile smears out. For y =L/2, the maximum difference in temperature along x is only 40 % of the difference, δT, on the back side. We can expect to see the effects of spatial temperature variations on the surface for features of the same order or larger than the substrate thickness.

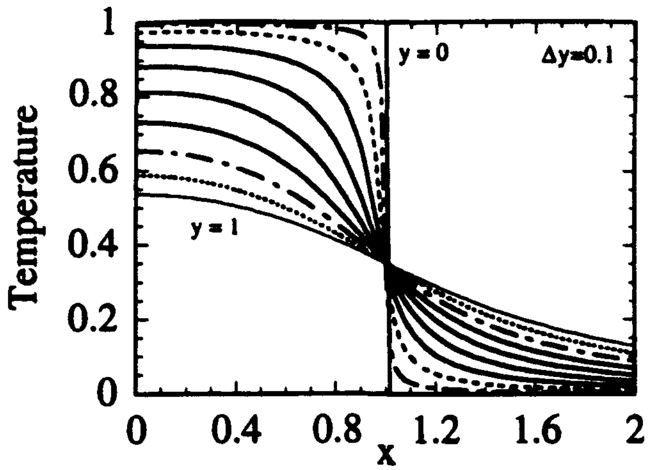

Fig. 2. Calculated temperature profile along x for various distances from the y axis. The temperature axis is scaled by dT and offset by T1 and the x and y values are in units of L/2.

2. Experimental Progress

2.1 Low-Threshold Edge Emitting Lasers

Before attempting to grow VCSEL laser structures, it is necessary to evaluate the quality of the material grown in the MBE system. We use the threshold current density of 100 μm wide broad area edge emitting lasers as a test of the material quality. We have grown and fabricated a InGaAs strained quantum well graded-index separate-confinement-heterostructure (GRIN-SCH) laser structure [5] with very low threshold current densities of ~200 A/cm^2. This is very comparable to the best reported values for short cavity lengths (~500 μm).

2.2 Wafer-Scale Reflectivity Spectra Measurement System

We have completed the construction of a wafer-scale reflectivity spectra measurement apparatus (see Fig. 3) for the characterization of the passive cavity test structures. The reflectometry measurement system can measure the Fabry Perot wavelengths across a 2" wafer. The spatial resolution of this system is determined to be as small as 100 μm. This system can automatically scan across the wafer, store the reflectance spectrum, and find the cavity mode at each point for an arbitrary grid size.

2.3 Patterned-Substrate MBE Growth of VCSEL Cavity

We have grown 11 wafers of the test structure described earlier with various substrate backings and substrate temperatures to establish the proper growth conditions. The substrate heating mechanism of the particular MBE system we are using is done by radiative heating from a filament. This is different form what is used in ref. 3. Hence, the methods we are investigating to create the temperature-dependent growth patterns are substantially different. Fig. 4 shows the various growth conditions we used including (a) substrate backed with a Si wafer having etched through holes, (b) substrate backed with a GaAs wafer having etched through holes, and (c) substrate backed with a GaAs substrate with etched grooves. The pattern sizes we have experimented range from 100 μm to 2 mm in size and the etched grooves are typically 200 μm deep. Two GaAs wafer thicknesses, 500 μm and 200 μm, were also experimented. Table I tabulates all the growth conditions we investigated. The first six wafers helped us to acquire experiences with the particular MBE growth system. Data presented here are from the last five wafers, which were grown in a sequence for controlled comparison.

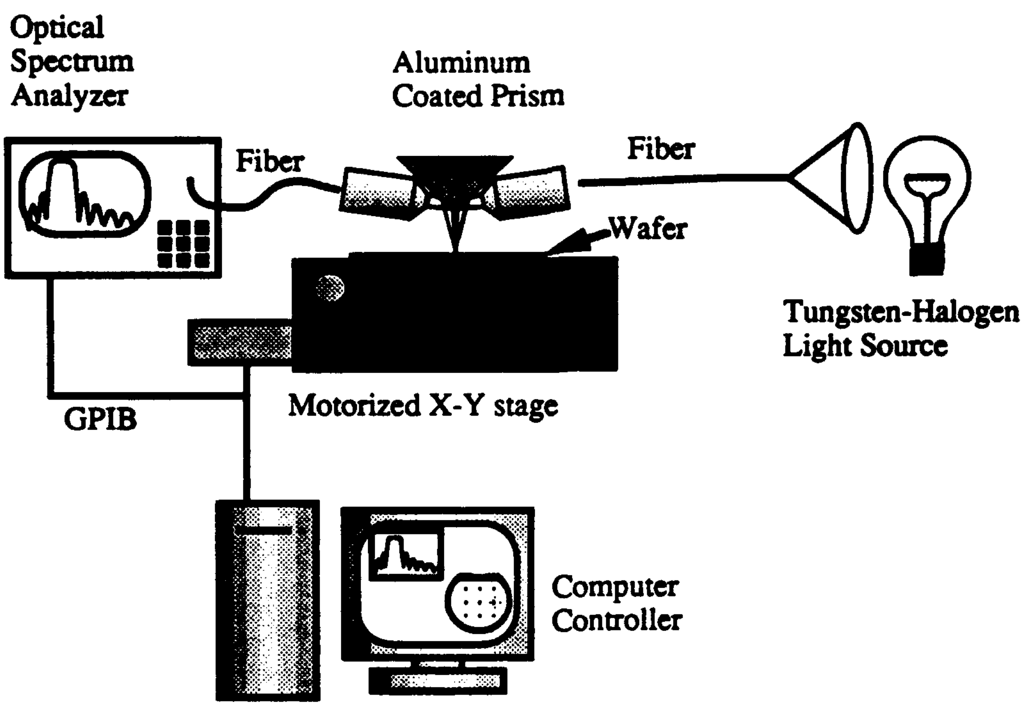

Fig. 3. Schematic of our reflectivity measurement apparatus

Wafer 3351 was grown at a substrate temperature of 600°C as a reference wafer. At this temperature, the growth rate for GaAs and AlAs should not be dependent on temperature and the growth should be uniform across the wafer. Wafers 3355-9 were all grown at an estimated temperature of 710°C, at which desorption of Ga from the surface is expected to happen resulting in a temperature-dependent GaAs growth rate. We grew these wafers in a sequence of 3355, 3356, 3357 (broken into pieces), 3351 and 3358. Growth calibrations were done only for the 3355.

We measured the reflectivity spectra of all wafers except for 3357. A variation of the Fabry-Perot (FP) mode wavelength as well as the Bragg reflector stop-band was observed across the wafer. Fig. 5 shows the FP mode wavelength as a function of position on the wafer for wafers 3355, 3356, 3351 and 3358. A continuous decrease in FP wavelength is seen when moving from the center of the wafer to the wafer edge. This is consistent with a ~1% beam flux nonuniformity in the MBE system. From these measurements we see that the fluxes from one growth to the next are gradually decreasing. However, we have not yet seen a periodic shift in the FP wavelength which we have attempted to induce in these wafers. In addition, the reference sample 3351 grown at a lower temperature was expected to show a FP wavelength at a longer wavelength by as much as 50 nm due to the absence of desorption. This was not observed. Instead, the reference sample follows the same trend as the others. This makes us conclude that none of the wafers were grown at a high enough temperature for the effects we are attempting to achieve.

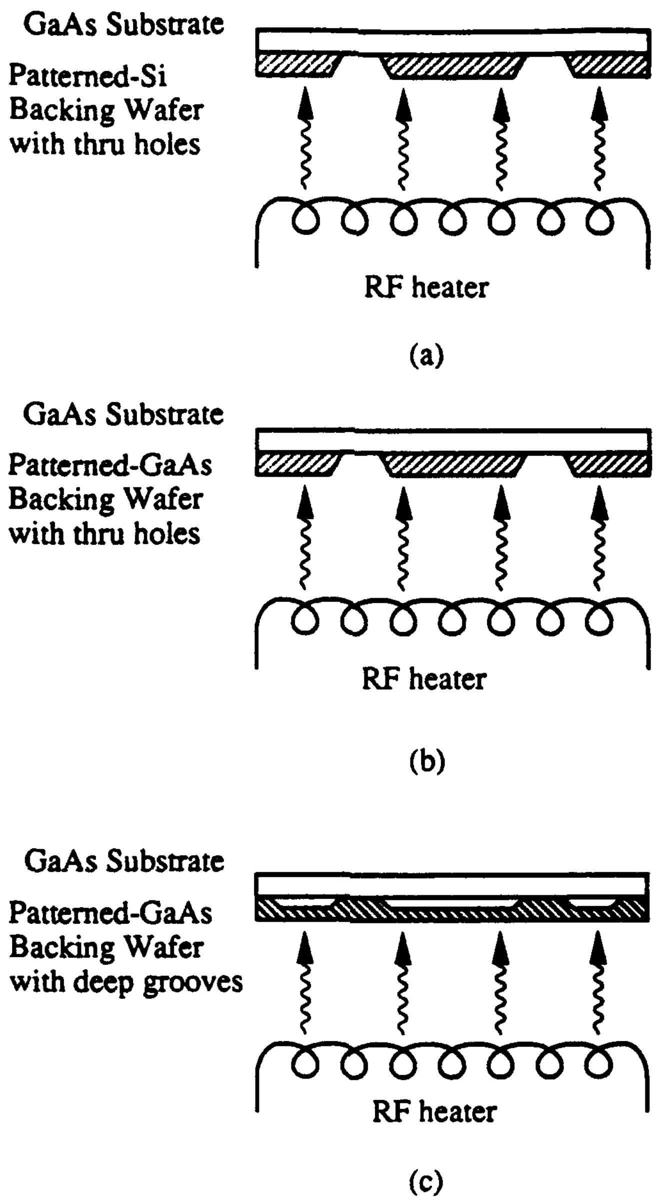

Fig. 4 Schematic of the various growth conditions we are investigating to induce a periodic growth variation on the wafer, including (a) substrate backed with a Si wafer having etched through holes, (b) substrate backed with a Ga wafer having etched through holes, and (c) substrate backed with a GaAs substrate with etched grooves. The substrate heating mechanism of this particular system is done by radiative heating from a filament.

Wafer #	Surface	Ts	Sub. Thick.	Backing Cond.	Backing Patterns
3086	hazy	730	500 µm	(c)	1-2mm wide grooves
3087	good	800	500 µm	(c)	1-2mm wide grooves
3088	good	705	500 µm	(a)	0.2mm wide thru holes
3198	hazy	730	500 µm	(c)	1-2mm wide grooves
3199	hazy	730	500 µm	(a)	0.2mm wide thru holes
3200	good	730	500 µm	none	
3351	good	600	500 µm	none,ref sample	
3355	good	730	500 µm	(c)	1-2mm wide grooves
3356	good	730	200 µm	(c)	1-2mm wide grooves
3357	good	730	500 µm	(b); fused	2mm wide thru holes
3358	good	730	500 µm	(a)	2mm wide thru holes

Table I Summary of all the wafers we grew with their relative growth conditions.

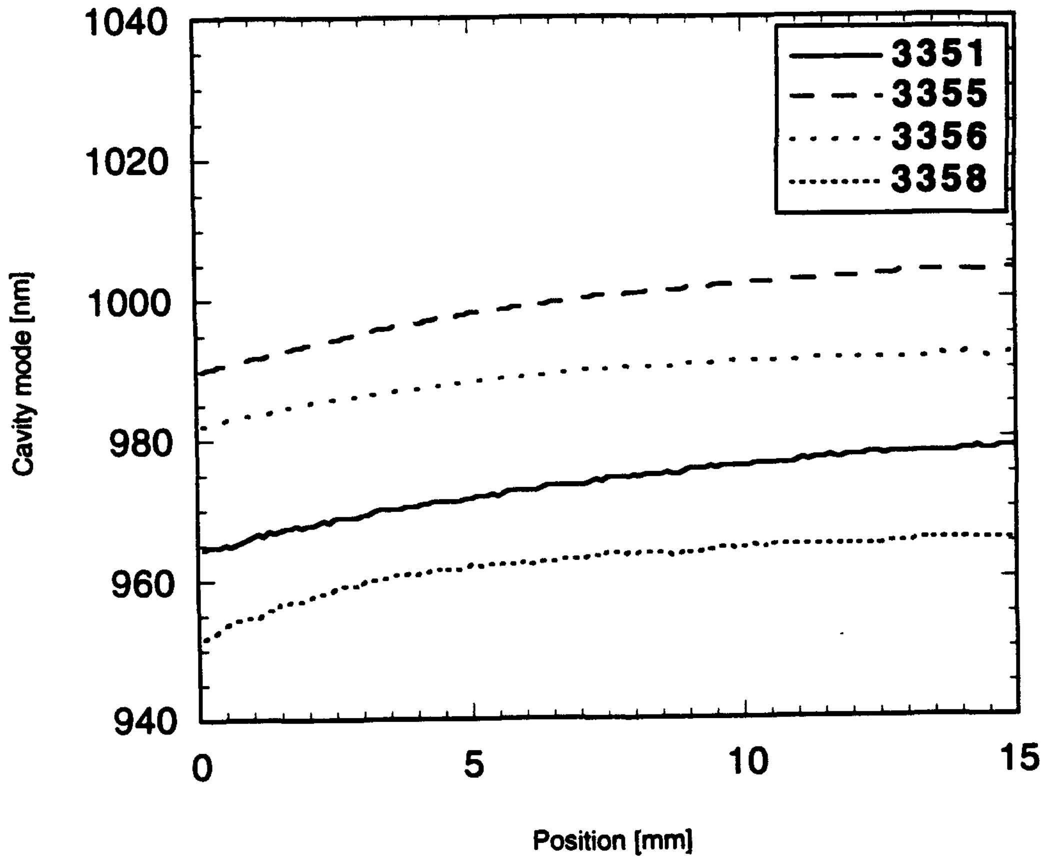

Fig. 5 Measured Fabry Perot wavelength vs. position along the x direction on the wafer, starting from the center of the wafer to 10 mm away from edge.

C. FUTURE DIRECTIONS

Currently, the most important step for us to achieve the pattern-induced growth variation is to be able to grow the material at an exactly-determined substrate temperature. Thus, we plan to accomplish this goal as the first step. In particular, we plan to use in-situ growth rate monitoring (with RHEED) to insure that the growth is taking place at a high enough substrate temperature to desorb source of the GaAs. We will also try to bond the growth substrate with the backing wafer with Indium to insure a good thermal contact as well as to absorb most of the substrate heater radiation. This should result in a higher surface temperature for growth as well as the desired surface temperature gradient. Then after we obtain the spatial variation of the FP wavelength of the test structures, we will fabricate VCSEL's using this technique.

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